Studies on collimation with hollow electron beams at Fermilab

A. Drozhdin, G. Kuznetsov, V. Shiltsev, G. Stancari,
D. Still, A. Valishev, L. Vorobiev (FNAL)
J. Smith (SLAC)

LARP Collaboration Meeting 13
Port Jefferson, NY
November 4, 2009

LARP

Motivation

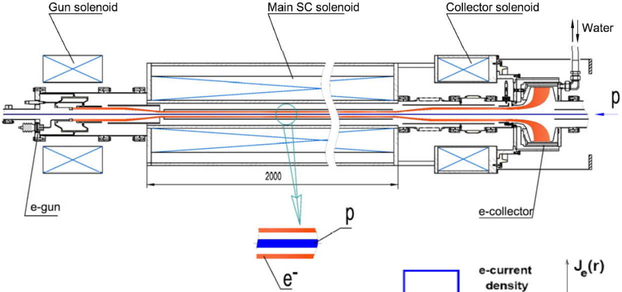
- Goals of collimation:
  1. reduce beam halo due to beam-beam collisions, intrabeam scattering, beam-gas scattering, rf noise, resonances, ground motion, ...
  2. concentrate losses in absorbers
- Conventional schemes:

  collimators (5-mm W at 5σ in Tev, 0.6-m carbon jaw at 6σ in LHC)

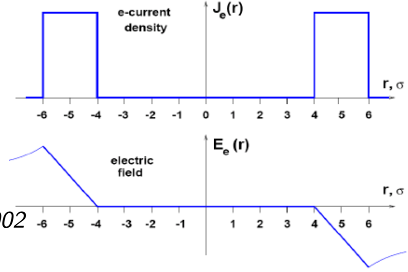
  absorbers (1.5-m steel jaws at 6σ in Tev, at 7σ in LHC)
- Hollow-electron-beam collimation is a candidate for improving LHC collimation/scraping at nominal intensities

Concept of hollow electron beam collimator (HEBC)

Cylindrical, hollow, magnetically confined, pulsed electron beam overlapping with halo and leaving core unperturbed



Halo experiences nonlinear transverse kicks



Shiltsev, BEAM06, Yellow Report CERN-2007-002
Shiltsev et al., EPAC08

Requirements and constraints

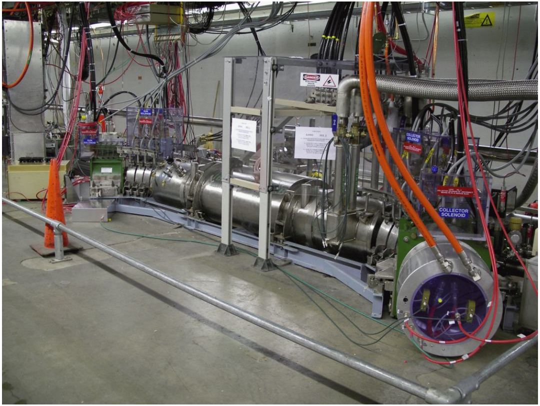
- Placement: $\sim 4\sigma$ + field line ripple ($\sim$0.1 mm)
- Transverse compression controlled by field ratio B_m/B_g; limited by min B_g (depends on current) and max B_m ($\sim$ 10 T)
- preferably large β_x, β_y, to translate kicks into large displacements
- if $\beta_x \neq \beta_y$, separate H and V scraping is required
- cylindrically symmetric current distribution ensures zero E-field on axis; if not, mitigate by:
    - segmented control electrodes near cathode
    - $\mathbf{E} \times \mathbf{B}$ plasma drift
    - different core/halo tunes

Hollow-beam collimation concept

Advantages

- electron beam can be placed closer to core ($\sim 3 - -4\sigma$)
- no material damage
- lower impedance, no instabilities
- position controlled by magnetic field, no motors or bellows
- gradual removal, reduction in loss spikes
- no ion breakup
- transverse kicks are not random $\rightarrow$ resonant pulsing, halo tune shift/spread
- estabilished technological and operational experience with Tevatron electron lenses: abort-gap clearing, beam-beam compensation

Existing Tevatron electron lenses (TEL1 and TEL2)



Typical parameters	
Peak energy	10 kV
Peak current	3 A
Max gun field B_g	0.3 T
Max main field B_m	6.5 T
Length L	2 m
Rep. period	21 μs
Rise time	<200 ns

Shiltsev et al., PRSTAB **11**, *103501 (2008)*

Hollow-beam collimation concept

Disadvantages

- kicks are small, large currents required
- alignment of electron beam is critical
- hollow beams can be unstable

Transverse kicks

$$\theta_{max} \simeq \frac{2\, I\, L\,(1 \pm \beta_e)}{r_{max}\, \beta_e\, c} \frac{1}{v_p\,(B\rho)_p} \left(\frac{1}{4\pi\epsilon_0}\right) \qquad \begin{array}{ll} - & \text{copropagating} \\ + & \text{counterpropagating} \end{array}$$

Example ($\mathbf{v}_p \cdot \mathbf{v}_e > 0$)

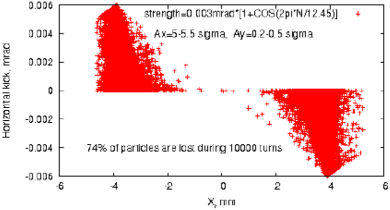
$I = 2.5$ A $\quad L = 2.0$ m $\quad \beta_e = 0.19$ (10 kV) $\quad r_{max} = 3.5$ mm (5σ in TEL2)

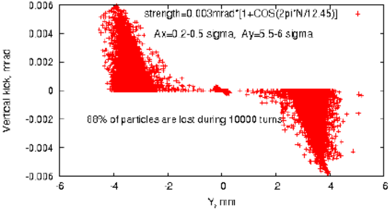
p energy (TeV)	0.150	0.980	7
kicks (μrad):			
hollow-beam max	2.4	0.36	0.051
collimator rms (Tevatron)	110	17	
collimator rms (LHC)			4.5

Simulation of HEBC in Tevatron

A. Drozhdin

- `STRUCT` code, complete description of element apertures, helices, rf cavities, sextupoles
- Halo defined as $[5\sigma < x < 5.5\sigma, 0.2\sigma < y < 0.5\sigma]$ or $[0.2\sigma < x < 0.5\sigma, 5.5\sigma < y < 6\sigma]$
- Hollow beam $5\sigma < r < 6.4\sigma$
- Resonant pulsing



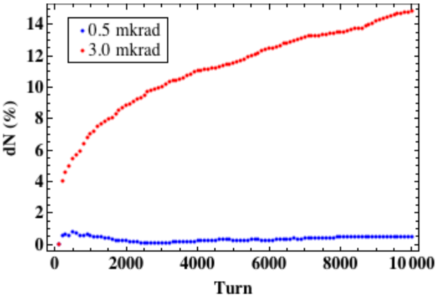


θ_{max}	Halo losses
0.3 μrad	28% in 200,000 turns
3.0 μrad	80% in 10,000 turns

Simulation of HEBC in Tevatron

A. Valishev

- `Lifetrac` code with fully-3D beam-beam, nonlinearities, chromaticity
- Simplified aperture: single collimator at 5σ
- Halo particles defined as ring in phase space with $3.5\sigma < x, y < 5\sigma$
- Hollow beam $3.5\sigma < r < 5\sigma$
- No resonant pulsing



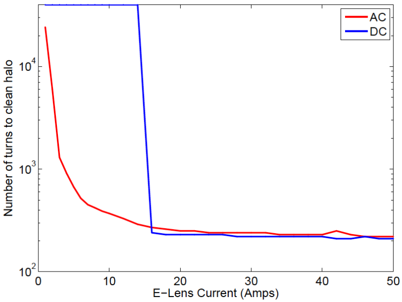
Halo losses vs turn number for maximum kick of 0.5 μrad and 3.0 μrad

Simulation of HEBC in LHC

Smith et al., PAC09, SLAC-PUB-13745

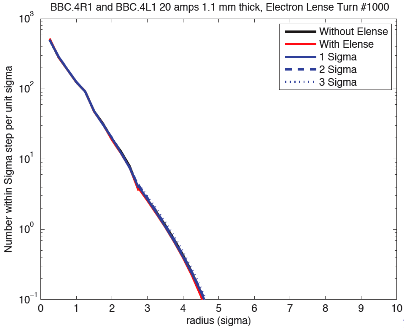
- Collimator at 6σ
- Beam halo defined as ring $4\sigma < x < 6\sigma$
- Hollow beam at $4\sigma < r < 6\sigma$

`first_impact` 1-D code:
cleaning $\equiv$ 95% hits collimator



`SixTrack` code:

- at 1.6 μrad, 1000 turns to clean
- HEBC allows to retract by up to 3σ

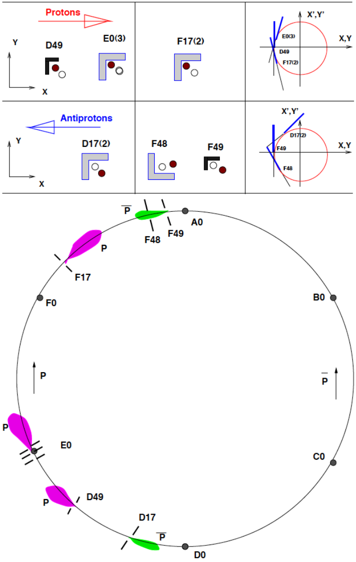


Collimation scenarios

Several collimation scenarios are being investigated:

- 'Staged' collimation scheme: HEBC $\rightarrow$ collimators $\rightarrow$ absorbers
  - HEBC probably too weak to replace collimators
  - increases impact parameter
  - allows collimators to be retracted
  - can act as 'soft' collimator to avoid loss spikes generated by beam jitter
- Effectiveness of betatron amplitude increase for halo particles:
  - transverse kicks are weak
  - tune shifts probably to small to drive lattice resonances
  - resonant kicks timed with betatron period are very effective

Tevatron studies at 980 GeV



Possible experimental demonstrations:

- hollow-beam alignment procedures
- effects on core lifetime
- losses at collimators, absorbers and detectors vs HEBC parameters: position, angle, intensity
- improvement of loss spikes in presence of beam jitter

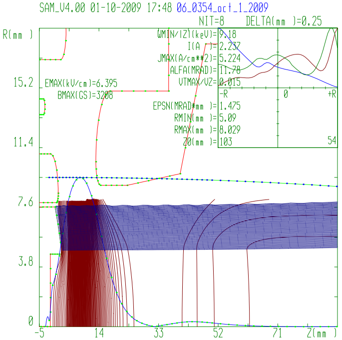
Recent activities

- Gaussian gun for beam-beam compensation studies installed in TEL2 on Jun 20; SEFT gun moved to test bench
- new TEL2 BPM readout
- designed hollow gun
- hollow gun produced by Hi-Tech Mfg using Heat Wave convex cathode, delivered on Aug 27
- installed hollow gun in test bench, measurements under way
- timed electron beam in TEL2, preliminary alignment with proton bunches

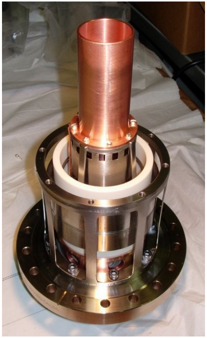
Design of 15-mm-diameter hollow gun

- several approaches to high-perveance hollow-beam design, eg immersed Brillouin cathodes (magnetron injection guns)
- present design based upon existing 0.6-in SEFT (soft-edge, flat-top) convex gun used in TEL2

Calculations with SAM code:



Mechanical design:

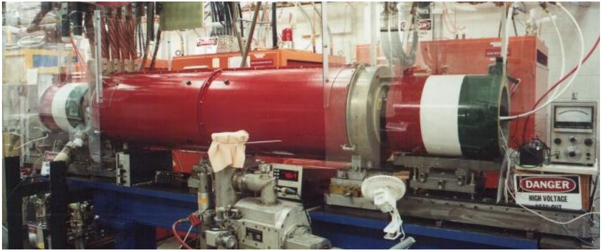


L. Vorobiev

G. Kuznetsov

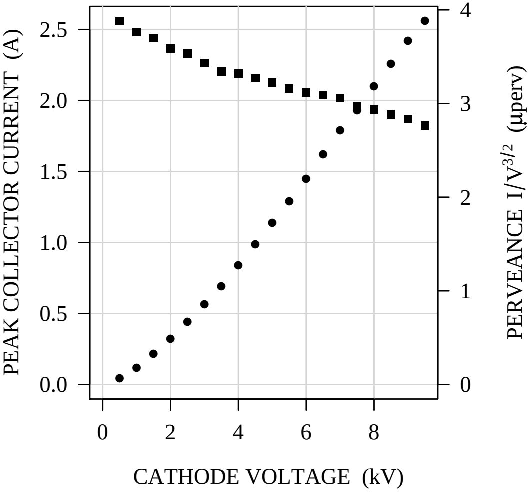
Test bench at Fermilab

Built to develop TELs, now used to characterize electron guns and to study plasma columns for space-charge compensation



- High-perveance **electron guns**: $\sim$amps peak current at 10 kV, pulse width $\sim\mu$s, average current $<$2.5 mA
- Gun / main / collector **solenoids** ($<$0.4 T) with magnetic correctors and BPM electrodes
- Water-cooled **collector** with 0.2-mm pinhole for profile measurements

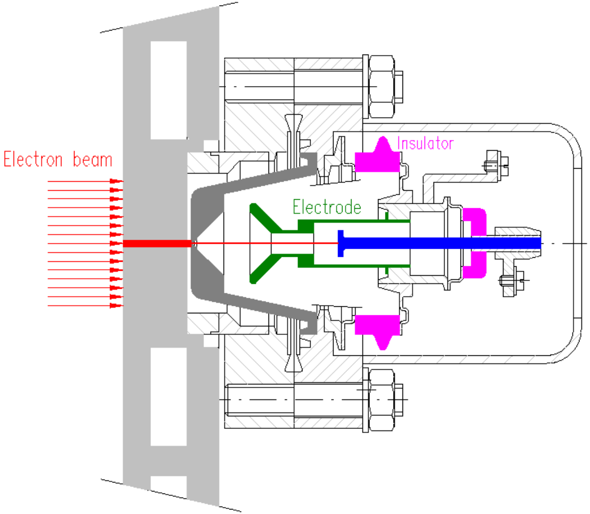
Current vs voltage of 15-mm hollow cathode



Filament heater: 66 W (1300 K)

Profile measurements

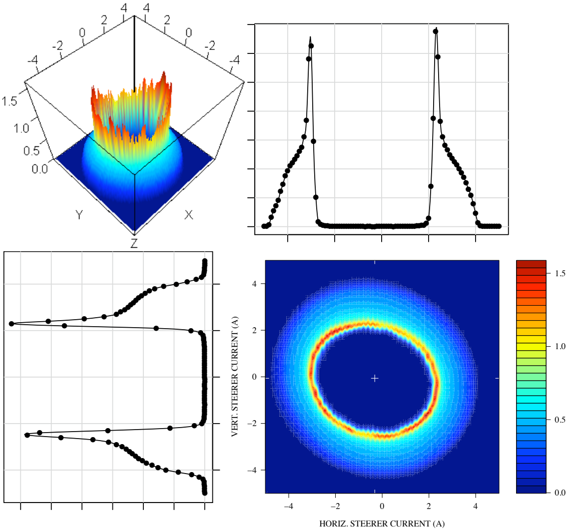
- Horizontal and vertical magnetic steerers deflect electron beam
- Current through 0.2-mm-diam. pinhole is measured vs steerer strength



Measured profile: 0.5 kV 44 mA 0.3 T

HOLLOW GUN
October 21, 2009

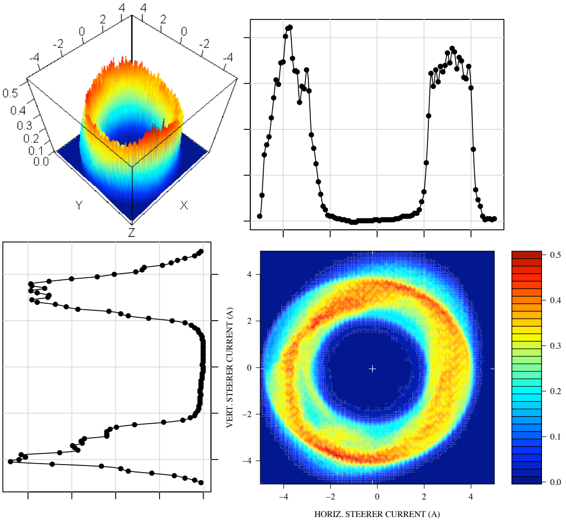
Vacuum: 2x10^{-8} mbar
Filament: 66 W (7.75 A)
Cathode voltage: -0.5 kV
HV PS current: 1.0 mA
Pulse width: 6 us
Rep. period: 0.6 ms
Peak current: 44 mA
Solenoids: 3-3-3 kG

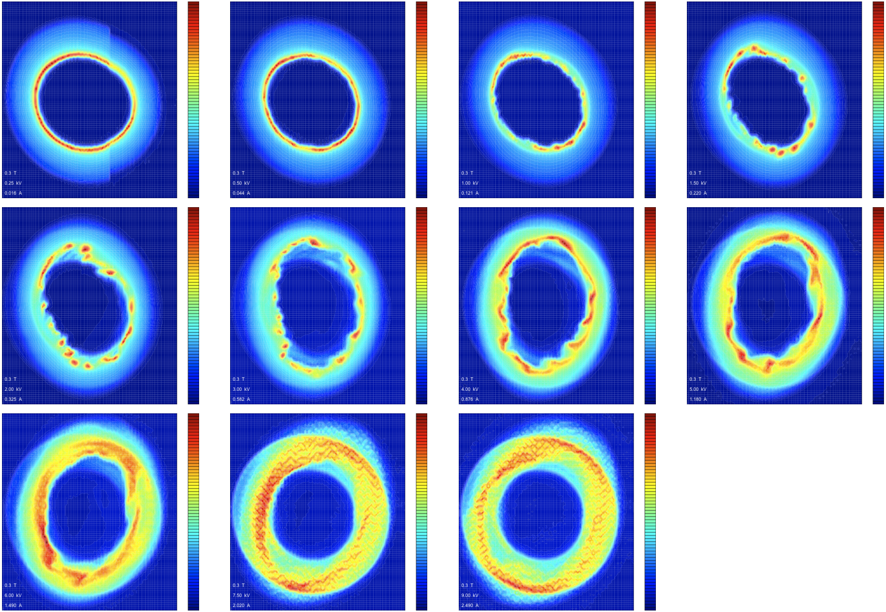


Measured profile: 9.0 kV 2.5 A 0.3 T

HOLLOW GUN
October 26, 2009

Vacuum: 2x10^{-8} mbar
Filament: 66 W (7.75 A)
Cathode voltage: -9.0 kV
HV PS current: 1.43 mA
Pulse width: 6 us
Rep. period: 80 ms
Peak current: 2.5 A
Solenoids: 3-3-3 kG




0.3 T
0.25 kV
0.016 A
0.3 T
0.50 kV
0.044 A
0.3 T
1.00 kV
0.121 A
0.3 T
1.50 kV
0.220 A
0.3 T
2.00 kV
0.325 A
0.3 T
3.00 kV
0.582 A
0.3 T
4.00 kV
0.876 A
0.3 T
5.00 kV
1.180 A
0.3 T
6.00 kV
1.490 A
0.3 T
7.50 kV
2.020 A
0.3 T
9.00 kV
2.490 A

Hollow-beam instabilities

- Profiles measured 2.5 m downstream of cathode
- Magnetic field kept constant at 0.3 T
- Space-charge forces are not uniform
- As current increases, vortices appear†
- Electron beam behaves like incompressible, frictionless 2D fluid*
- $\mathbf{E} \times \mathbf{B}$ drift velocities depend on r
- Typical plasma slipping-stream ('diocotron') instabilities arise
- Scaling with magnetic field and stabilization under study
- $\mathbf{E} \times \mathbf{B}$ drift does tend to restore symmetry

† *Kyhl and Webster, IRE Trans. Electron Dev. ED-3, 172 (1956)*
* *Levy, Phys. Fluids 8, 1288 (1965)*

Next steps

- Simulations:
  - code comparison under common scenarios
  - performance vs lattice parameters
  - uneven B-field lines
  - realistic current profiles (smooth, asymmetric, ...)
- Test bench:
  - Complete characterization of 15-mm hollow cathode
  - Study stability of hollow beam
  - Design larger cathode
- Tevatron:
  - Calibrate TEL2 BPMs with protons, electrons and antiprotons
  - Align Gaussian electron beam with protons in TEL2
  - Test abort-gap clearing
  - Measure tune-spread changes with Gaussian gun
    (beam-beam compensation project)
  - Install hollow gun in TEL2 (next few months?)
  - Start parasitical and dedicated studies